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Trends in Seasonal Sea Ice Duration in Southwestern Hudson Bay

WILLIAM A. GOUGH,[1] ADAM R. CORNWELL[2] and LEONARD J.S. TSUJI[3]

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ABSTRACT. The southwestern region of Hudson Bay is one of the last areas in the Hudson and James Bay lowlands region to become free of sea ice in the spring. This late breakup is due to the effects of winds and currents. By analyzing time series with three different statistical techniques, we found a statistically significant increase in the length of the ice-free season in this region from 1971 to 2003. Much of this increase was attributed to earlier breakup of the ice, which is consistent with increased spring temperatures in this region. The onset of breakup advanced by at least three days per decade over the study period.

Key words: Hudson Bay, sea ice, breakup, climate change

RÉSUMÉ. La partie sud-ouest de la baie d'Hudson est l'une des dernières zones des basses terres de cette baie et de la baie James à se libérer de la banquise au printemps. Cette débâcle tardive est due aux effets des vents et des courants. En analysant des séries chronologiques à l'aide de trois techniques statistiques différentes, on a découvert que, de 1971 à 2003, la région a connu une augmentation sensible dans la durée de la saison d'eau libre. Une grande partie de cette augmentation a été attribuée à une débâcle précoce, ce qui va de pair avec une hausse des températures printanières dans la région. Le début de la débâcle a avancé d'au moins trois jours par décennie au cours de la période d'étude.

Mots clés: baie d'Hudson, banquise, débâcle, changement climatique

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INTRODUCTION

Recent studies have shown that both the extent (Smith, 1998; Parkinson et al., 1999) and the duration (Etkin, 1991; Stirling et al., 1999) of the sea-ice cover in Hudson Bay have been decreasing over the past few decades, likely as a result of climate change (i.e., increasing surface air temperature) or low-frequency climate oscillations (Mysak and Venegas, 1998; Venegas and Mysak, 2000). In addition, Stirling et al. (1999) reported on long-term trends in the population ecology of polar bears in the western Hudson Bay region of northern Canada in relation to changing regional climate.

We provide an overview of the physical geography of Hudson Bay so that the "normal" patterns of ice formation and breakup can be understood. The prevailing winds, particularly in the southern portion of the Bay, are westerly. At the onset of winter, from late October to late November, these winds are relatively cold, originating over the landmasses of northern Manitoba and Nunavut. Freeze-up begins at the west side of the Bay and spreads eastward, especially along the south shore (Gough and Allakhverdova, 1999; Gough and Wolfe, 2001).

Open water first appears in James Bay, at the southern end of Hudson Bay close to the western shoreline, where it is due to warm winds, and also in the eastern region of the Bay, where it results from spring runoff (Etkin, 1991). Ice that melts in the southern part of Hudson Bay is replaced through ice advection from the north. As a result, the last place to break up in the spring is often the southwestern region of Hudson Bay, our study area. Changes in the ice-cover pattern are expected to be mainly the result of atmospheric forcing (Wang et al., 1994; Gough and Allakhverdova, 1999).

As noted by Wang et al. (1994) and others, interannual variability—driven largely by the El Niño/Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO)—has the potential to influence the ice cover on the Bay. Researchers have investigated correlations between polar sea ice and atmospheric oscillations such as ENSO and NAO. Wang et al. (1994) analyzed the sea-ice cover in Hudson Bay, Baffin Bay, and the Labrador Sea; a composite of summer ice cover in 12 Low/Wet ENSO events between 1953 and 1988 was compared to the means for the entire period. For Hudson Bay, relatively heavy ice conditions in the ENSO composite were reported. A statistical analysis showed that the positive correlation between the Low/Wet ENSO index and the summer ice cover in the Bay was statistically significant. A similar correlation was found between summer ice cover and the Azores High/Icelandic Low phase of the NAO, which is

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[1] Department of Physical and Environmental Sciences, 1265 Military Trail, University of Toronto at Scarborough, Toronto, Ontario M1C 1A4, Canada; gough@utsc.utoronto.ca

[2] Department of Geography, University of Toronto, 100 St. George Street, Toronto, Ontario M5S 3G3, Canada

[3] Department of Environment and Resource Studies, University of Waterloo, 200 University Avenue West, Waterloo, Ontario N2L 3G1, Canada

characterized by strong west-northwest winds over the Bay (also see Parkinson et al., 1999).

Wang et al. (1994) also noted a strong correlation between summer sea ice and the volume of runoff in the previous year. Mysak et al. (1996) continued this investigation by focusing on three simultaneous ENSO and NAO events in 1972–73, 1982–83, and 1991–92. They also found a strong correlation between these events and the surface air temperatures of the following summer. As expected, the decreased atmospheric temperatures had an immediate effect on the ice cover, with the breakup coming very late in 1973, 1983, and 1992. Yi et al. (1999) used a composite map method similar to that of Wang et al. (1994) and a singular value decomposition to analyze a time series of sea-ice fluctuation across the Arctic. It was found that the time series correlated well with the NAO. In addition, a clear decreasing trend in ice cover overall was noted, most notably in the region east of Greenland.

In addition to these atmosphere-driven oscillations, severe summer ice conditions have been linked to volcanic activity (Catchpole and Hanuta, 1989). The eruption of Mt. Pinatubo in 1991 was followed by a heavy ice year (late breakup in Hudson Bay).

Computer simulations project that the equilibrium global average temperature will rise 2˚–4˚C in response to an equivalent doubling of atmospheric CO_2; it is also predicted that this temperature increase will likely be realized within the next 50–60 years (Harvey, 1999). However, this is a globally averaged increase; it is expected that the warming will be even greater at high latitudes because of the ice-albedo and atmospheric lapse rate feedbacks (Harvey, 1999). These effects could cause high-latitude warming to be larger than the global average by a factor greater than two. Etkin (1991) suggests that a 1˚C warming could advance breakup by over 14 days in the eastern area of the Bay and by six to eight days in the southwest. Gough and Wolfe (2001), using computer simulations, suggest the cessation of seasonal sea ice in the region as early as 2050.

In this work, we examine the trends of freeze-up and breakup in southwestern Hudson Bay, a region characterized by the longest surviving seasonal sea ice in Hudson Bay and a currently thriving polar bear population. These trends will be examined using three different statistical techniques to detect secular trends and to account for sea-ice variability induced by ENSO, NAO, and volcanic activity.

MATERIALS AND METHODS

Study Area

Hudson Bay (together with James Bay) is a large body of salt water located in northern Canada. It borders on three provinces (Manitoba, Ontario, and Quebec) and the territory of Nunavut (Fig. 1). Most of this body of water is separated from the rest of the ocean by land masses; exchange occurs only through narrow channels at the north end to Foxe Basin and Hudson Strait. As a result, Hudson Bay behaves like a relatively closed system (Etkin, 1991; Gough and Allakhverdova, 1999).

Hudson Bay (referred to hereafter as the Bay) has a surface area of 83×10^4 km^2 and an average depth of 120 m (Prinsenberg, 1984). The Bay is ice-free in the summer and freezes over in the winter; typically it is completely covered in ice from January to May and is ice-free from mid-August to late October (Wang et al., 1994). Thus, in the summer months the Bay creates a general marine climate in the surrounding area, while in the winter it is insulated by ice and snow and permits cold polar air masses to extend south into central Canada (Prinsenberg, 1984).

Determining Freeze-up and Breakup Dates

Ice-cover data were obtained from the Canadian Ice Service of Environment Canada. Data consisted of regional ice analyses mapped out weekly from 1971 to 2003 (e.g., Fig. 1), with some gaps as will be noted. This data set was created using infrared satellite data (AVHRR), microwave satellite (RADARSAT) data, aircraft and ship observations, and surface observations. In addition, aircraft reconnaissance for navigation purposes occurs from late spring to ice breakup, thus making the breakup data particularly robust. The charts are issued weekly, producing precision and accuracy of one week.

For the purpose of determining breakup and freeze-up, the study region, marked in darker lines, was approximated to lie south of 58˚ N latitude and between 82˚ and 89˚ W longitude. This region, as mentioned previously, is one of the last areas to break up. It is directly adjacent to the denning areas of one of two populations of polar bears in Hudson Bay. Sea-ice conditions for the other population of bears (near Churchill, Manitoba) have been examined in Stirling et al. (1999).

Following the method of Stirling et al. (1999), which was adopted from Etkin (1991), we arbitrarily defined the breakup and freeze-up dates by the point at which the majority of the ice cover decreased (or increased) to 5/10. Specifically, we did this by breaking the region down into boxes of $0.5˚ \times 0.5˚$. If more than half of the boxes in the region were covered by 5/10 ice or less, the region was considered to have broken up (or not yet frozen). In addition, because the ice freezes along the shoreline first, the region was considered to have frozen up if the grid boxes closest to shore were covered by more than 5/10 ice. The resulting dates for breakup and freeze-up are recorded in Table 1. Note that the dates are only accurate to within one week and that freeze-up dates are unavailable for several years when the ice did not freeze until after the sampling period ended. For the missing years in the 1970s, there were no analyses in December. In the 1990s, the analyses stopped after the first week of December.

Statistical Approach

Simple Linear Regression: We chose the parameters β_0 and β_1 for the deterministic equation $Y = \beta_0 + \beta_1 T + \varepsilon$,

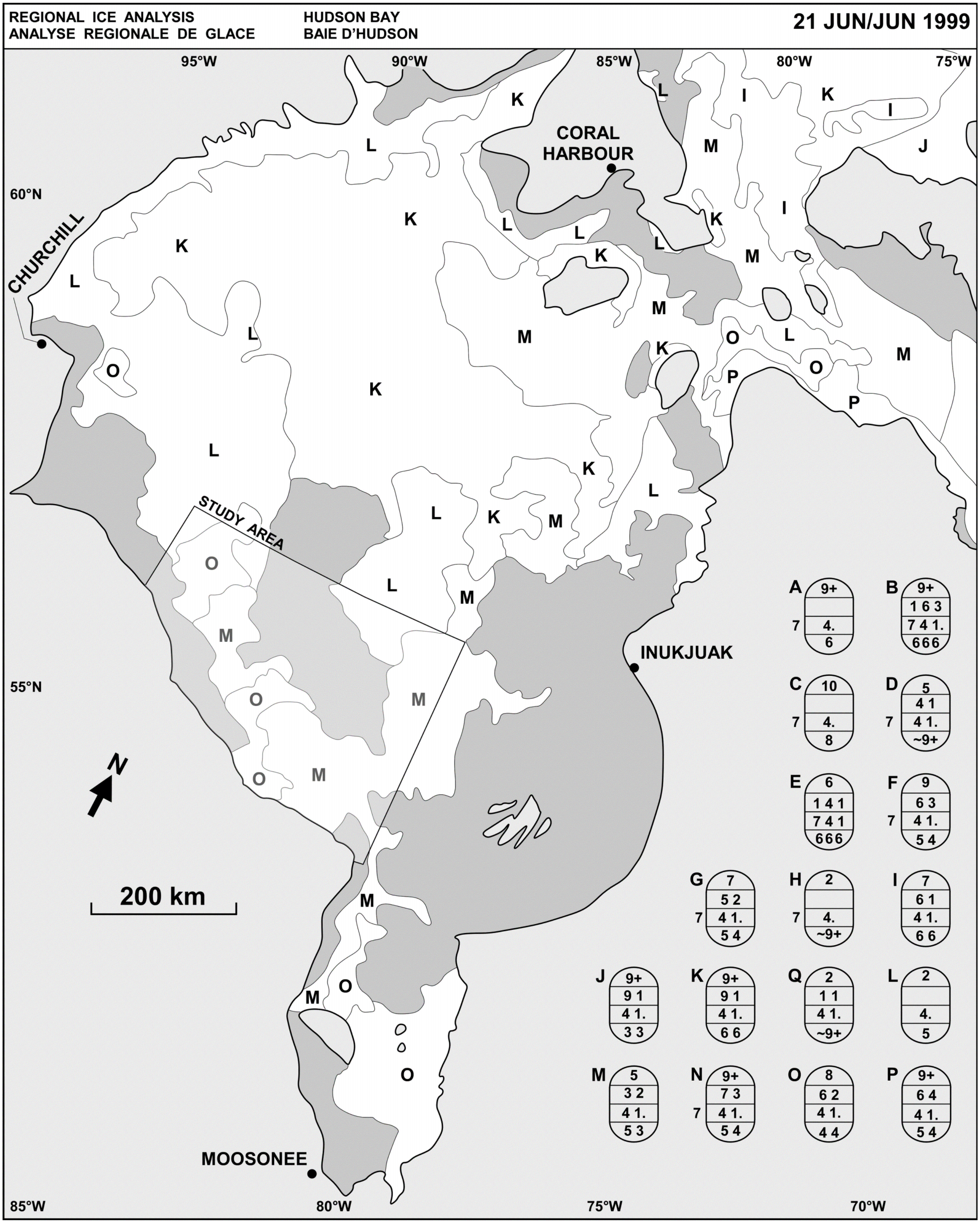

FIG. 1. Sample ice chart, with study area indicated by straight dark lines.

TABLE 1. Critical ice-cover dates for the study region.

Year	Breakup Date	Freeze-up Date	Days in Melt Season
1971	July 19		
1972	August 4	November 24	112
1973	July 30		
1974	July 22	November 18	119
1975	July 21		
1976	July 26	December 6	133
1977	July 18		
1978	July 9	November 19	133
1979	July 22	November 25	126
1980	July 27	November 30	126
1981	July 26	December 6	133
1982	July 25	November 28	126
1983	August 2	December 6	126
1984	July 26	November 15	112
1985	August 8	November 21	105
1986	August 3	November 16	105
1987	July 26	November 22	119
1988	July 17	December 4	140
1989	August 6	December 3	119
1990	July 8	November 25	140
1991	June 30	November 24	147
1992	August 23	November 22	91
1993	July 11	November 21	133
1994	July 24		
1995	July 23	November 26	126
1996	July 21	December 1	133
1997	July 17	December 1	137
1998	June 29		
1999	June 14		
2000	July 31		
2001	July 2	December 24	175
2002	July 22	November 25	126
2003	July 21		

where Y is the dependent variable (breakup date), T is the independent variable (year), and ε is normally distributed random noise. Parameter selection was done by minimizing the sum of the squares of the deviations of the observed values from those predicted. In other words, estimates were chosen to minimize the sum:

$$\sum_{u=1}^{n} \left(Y_u - \hat{Y}_u \right)^2$$

The slope of the resulting linear regression line then represented the trend in the data. A confidence test of the resulting trend was performed using a Student's t distribution test. The null hypothesis that $\beta_1 = 0$ can be checked according to the test statistic,

$$t = \frac{\hat{\beta}_1}{S_{\hat{\beta}_1}}$$

where the S term is the estimated standard deviation of the estimated slope. This test statistic has a Student's t distribution with $(n - 2)$ degrees of freedom, provided that T and Y have a linear relationship and that ε is random and normally distributed (Mendenhall, 1987).

Mann-Kendall Test: A more practical test for the existence of a trend is the nonparametric Mann-Kendall test. The utility of the Mann-Kendall test is that it is considered robust, being insensitive to outliers and power transformations (Helsel and Hirsch, 1992). The test does require that there be no serial correlation in the time series; the correlogram of the data shows that this is indeed the case, as there is no autocorrelation beyond lag zero.

This test considers whether Y values tend to increase or decrease with T (time, in this study) by computing Kendall's S statistic from the data pairs of Y and T. S is the sum of the signs of the slopes of all possible combinations of two points from the data set. This could be otherwise described by setting $S = P - M$, where P is the number of times $Y_i < Y_j$ for all $i < j$ and M is the number of times $Y_i > Y_j$ for all $i < j$. If S is significantly different from zero, Y is monotonically increasing or decreasing over time.

A test statistic can be used to check for the statistical significance of S. For relatively large samples ($n > 10$), a normally distributed approximation Z_S can be constructed, where

$$Z_S = \begin{cases} \frac{S-1}{\sigma_S}, S>0 \\ 0, S = 0 \\ \frac{S+1}{\sigma_S}, S<0 \end{cases}$$

σ_S is a standard deviation that depends on the sample size; it must also be corrected for "ties" in the data ($Y_i = Y_j$). If t_i is the number of ties of extent i, then σ_S can be calculated as:

$$\sigma_S = \sqrt{\frac{1}{18}\left[n(n-1)(2n+5) - \sum t_i(i)(i-1)(2i+5)\right]}$$

A p-statistic for Z_S can then be constructed from a table of the normal distribution (Helsel and Hirsch, 1992). If a trend is present, the slope can be estimated nonparametrically using a Kendall-Theil line. In this method, the estimate of the slope of the long-term trend is given by the median of all possible pairwise slopes, i.e.:

$$\hat{\beta}_1 = median\left(\frac{Y_j - Y_i}{T_j - T_i} \right) \text{for all possible } i < j$$

Multivariate Autoregression with SAS: A key problem with the simple linear regression analysis described earlier was the assumption that the variation from the linear relationship was essentially random noise.

If one also takes into account that the 1991 eruption of Mt. Pinatubo in the Philippines was a likely contributor to the anomalously late breakup in 1992, a superior analysis would include these variables in the regression. This can be accomplished using the *autoreg* procedure of the SAS statistical software package. The *autoreg* procedure can perform a multivariate regression analysis on time-series data. Indices for ENSO and NAO, taken from data sets of the Climate Research Unit of the University of East Anglia, UK, were available for our use. Consistently with Wang et al. (1994) and Mysak et al. (1996), we used the NAO index for the winter months (December to March). A dummy variable was also supplied to *autoreg* to indicate the Pinatubo eruption, essentially a step function for 1992.

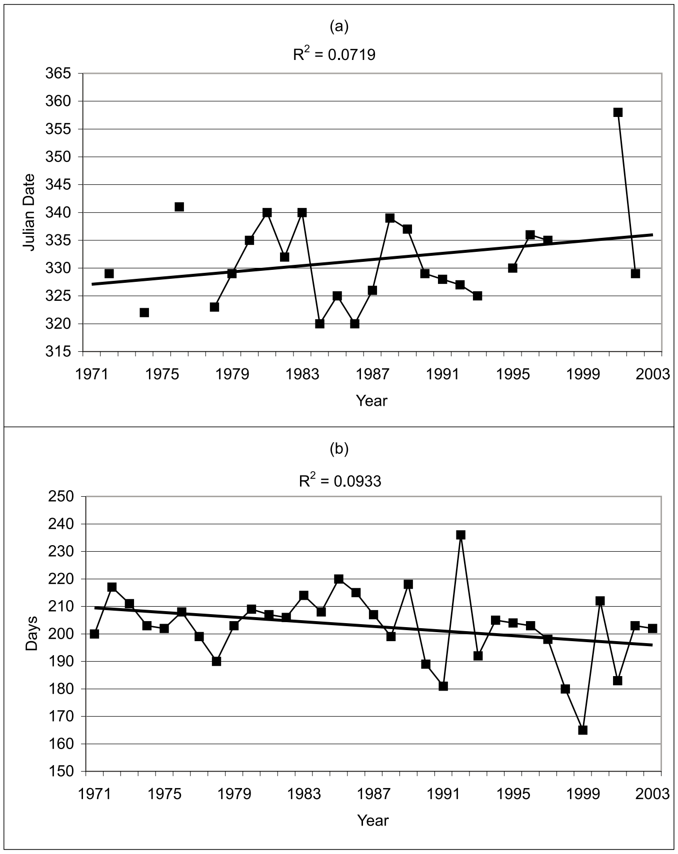

FIG. 2. Time series of (a) freeze-up and (b) breakup dates for southwestern Hudson Bay.

The three time series (ENSO, NAO, and Mt. Pinatubo) are the independent variables, and the time series for freeze-up dates is the dependent variable.

RESULTS

Simple Linear Regression

Figure 2 plots the time series of (a) freeze-up and (b) breakup dates, together with the linear regression trend lines. There is no significant trend for the freeze-up dates. For the breakup dates, the estimated slope of this line $\hat{\beta}_1$ is approximately -0.424 (days/year); that is, ice is breaking up 0.424 days earlier each year. The coefficient of determination, R^2, is approximately 9%, suggesting that much of the variability either must be explained by other mechanisms or is random. The estimated standard deviation of this slope parameter is 13.0, yielding a test statistic $t = -1.79$. The critical value for the 90% confidence interval of the two-tailed Student's t distribution with 31 degrees of freedom is $t_{crit} < 1.699$; since $t < -t_{crit}$, the null hypothesis can be rejected with 90% confidence. However, in a real process such as this one, Y may not be linearly dependent on T, or ε may not be random and normally distributed; in fact, both ENSO and NAO affect Y but are not random events. Nevertheless, there is indication of a trend towards earlier breakup of ice cover in our study region.

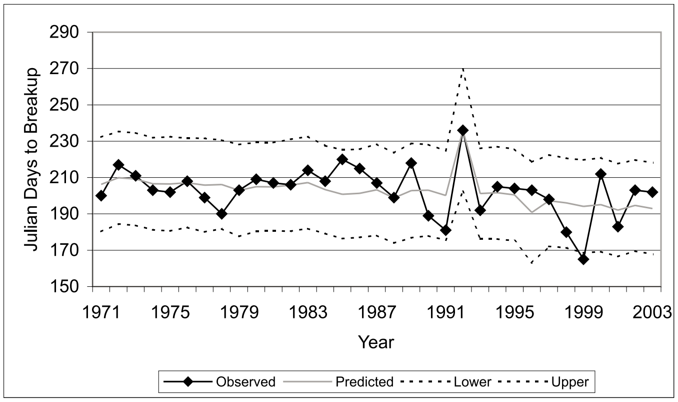

FIG. 3. Multivariate analysis with 95% confidence intervals. The independent variables are time series for ENSO, NAO, and volcanic activity.

In Figure 2b, the sharp peak in 1992 not only coincides with the strong ENSO and NAO events discussed by Mysak et al. (1996), but also represents the first summer following the eruption of Mt. Pinatubo in the Philippines. The aerosol emissions from this eruption had a cooling effect on temperatures around the world (Harvey, 1999). It seems quite likely that this eruption was at least partially responsible for the anomalously late breakup in 1992. When this potential outlier was removed from the time series, the slope increased to -0.485, i.e., breakup is occurring almost half a day earlier each year.

Mann-Kendall Trend Significance

The Mann-Kendall test is more appropriate for this time series, since it does not require any dubious assumptions about the data. Computing Kendall's S from ice breakup data yields $S = -106$. Using the normally distributed approximation $Z_S \cong -1.63$ and the one-sided quartile of 0.9484 yields a p-statistic of $2(1-0.9484) \cong 0.103$. We can therefore assert that there is a trend in the time series with 90% confidence, which is similar to the confidence level obtained from linear regression analysis. The estimated magnitude of the trend, using the Theil slope method, is -0.286 (days/year).

Interestingly, while this method is supposed to be relatively insensitive to outliers, the results do change significantly if the data point from 1992 is removed from the series. The new results are: $S = 116$ and $Z_S \cong -1.86$, which produces a p-statistic of 0.063, indicating that the trend now has 94% confidence. The estimated magnitude of the trend increases to -0.300 (days/year).

Multivariate Autoregression with SAS

The predictions of the multivariate regression are plotted in Figure 3. It can be seen that some features of the observed time series are modeled well, but others are not. However, the observed series does stay within the 95% confidence limits for the most part. The estimated relationship between breakup date and time is -0.743 (days/year), with a standard error of 0.220. This implies that we can approximate a 95% confidence interval by multiplying the standard error by 2.039 (from a t-table with n - 1 = 32 degrees of freedom; Cody and Smith, 1985); therefore, we can be 95% confident that the slope lies between -0.093 and -0.991, which is a relatively large interval. Moreover, the analysis yields a probability for the null hypothesis (that the slope equals zero) of 0.020, indicating that we are over 98% confident that breakup has been occurring earlier through the years.

We are less confident in the relationship between breakup dates and ENSO and NAO. The null hypothesis probabilities for these indices are 0.548 and 0.401, respectively. In other words, the increase in the statistical significance is largely the result of including the effect of Mt. Pinatubo in 1992. However, we are probably justified in including ENSO and NAO in the analysis since the confidence and error bounds of the breakup-time relationship have improved. Clearly some natural variability remains unaccounted for in this analysis.

DISCUSSION

Climate Change in the Southwestern Hudson Bay and Northwestern James Bay Region

The most reliable method used in the present study to examine freeze-up and breakup dates was the Mann-Kendall test. This is a nonparametric test that does not rely on assumptions of linear relationships and normally distributed noise. By this measure (and neglecting the 1992 outlier), we can be 94% confident that the ice in the southwestern region of Hudson Bay and the northwestern region of James Bay has been breaking up earlier in recent years. Furthermore, a Kendall-Theil robust line approximation of the strength of the relationship estimates that the days to breakup are decreasing by 0.300 (days/year). These results are consistent with those of the parametric regression approaches.

Multivariate analysis does suggest a relationship between the duration of ice cover and atmospheric oscillations, that is, ENSO and NAO and volcanic eruptions. Breakup appears to occur later during years with Low/Wet ENSO episodes (SOI < 0) and strong westerly NAO episodes (NAO > 0), which is consistent with ice-extent studies by Wang et al. (1994) and Mysak et al. (1996). However, the statistical significance of this apparent relationship is unclear for ENSO and NAO, and the higher statistical significance appears to be mainly the result of including the 1992 Mt. Pinatubo volcanic eruption.

Given the lack of temperature observations, this study uses the passage of years as a proxy for suspected warming temperatures. A future study investigating the cumulative impact of temperature change through the spring season could shed more light on the impact of temperature changes on ice-cover breakup. The work of Gagnon and Gough (2002) points in this direction. They found, for example, a statistically significant increase in spring temperatures in five northern Ontario locations (including Moosonee), which is consistent with the earlier breakup dates. At these locations, autumn temperatures either were decreasing significantly or had no significant trend, consistent with the lack of any trend in the freeze-up dates.

Identification of Long-Term Trends

Other researchers have identified long-term trends in sea-ice dynamics in the Arctic. Maslanik et al. (1996) used satellite records of ice cover from 1978 through 1995. Although their area of study did not include Hudson Bay or James Bay, they showed that the perennial ice pack was 9% smaller in 1990–95 than in 1978–89. Similarly, Smith (1998) used satellite data (passive microwave) to examine ice cover in the polar region, recording the dates when melting began and ended. An interesting finding was that the length of the melt season had increased by an average of 5.3 days per decade over the period 1979–96. Parkinson et al. (1999) also used satellite data to analyze ice-cover trends in nearly all Arctic waters, including Hudson Bay, for the period 1979–96. They found a statistically significant trend of -34 000 km^2/year in sea-ice extent over the Northern Hemisphere as a whole, with a much smaller and less statistically significant trend in Hudson Bay.

The results of the present study are in general agreement with the above-mentioned studies. More specifically, a trend towards earlier breakup dates (with no trend in freeze-up dates) was also found by Stirling et al. (1999), who examined a 20-year data set (1979–98) for the area directly north of the region presently studied.

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